REFERENCE FREQUENCY TRANSMISSION OVER OPTICAL FIBER

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ABSTRACT

An experiment has been performed in which the stability of a fiber-optic link 14 kms long, was measured and found to be 1.5 X 10^{-15} for 1000 seconds averaging time. A 100 MHz reference frequency generated by a hydrogen maser frequency standard was transmitted over a single-mode fiber-optic link from Deep Space Station (DSS) 13 to DSS-12 and back again. The stability of the fiber-optic link was measured by comparing the output signal to the input signal in a JPL designed frequency stability analyzer. The experiment was performed in April 1986 at the Goldstone Deep Space Communications Complex (DSCC) near Barstow, California, part of NASA's Deep Space Network (DSN).

This paper will discuss the significance of stable reference frequency distribution in NASA's Deep Space Network (DSN) and will describe the fiber-optic link, the measurement method and equipment, and the results of the experiment.

I. Introduction

The Deep Space Network (DSN) has very stringent requirements for precise frequency and time. JPL uses hydrogen maser frequency standards, which are stable to better than 1 X 10^{-15} for 1000 seconds averaging time, in the DSN to meet these requirements. The future goal for frequency stability in the DSN requires improvements of up to two orders of magnitude over the present capability.

Such stringent requirements demand the development of a new generation of ultra-stable sources of frequency, such as trapped ion frequency standards and superconducting cavity stabilized oscillators. The performance level of these new standards will place extreme stability requirements on the transmission systems that must distribute these reference frequencies to the users.

Group delay variations occur in all cables and make ultra-stable frequency distribution difficult. As the group delay changes in a cable it causes the frequency of a transmitted signal to be offset by an amount proportional to the rate of change of the group delay. Temperature changes and changes in mechanical stress, usually as a result of bending, are the major causes of group delay change in cables.

Currently, coaxial cables are used to distribute precise reference frequencies from a single hydrogen maser within a station to a number of local users. It is clear, however, that distribution of precise frequency and time from a centralized location to remote users within an entire complex offers some attractive benefits. These benefits include the

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possibility of arraying stations for experiments such as connected element interferometry, an economy in the number of frequency standards within the complex, and a redundancy in frequency standards. This latter feature will guarantee the availability of hydrogen masers during critical periods such as spacecraft encounters with major planets. It will also permit continuous characterization of the performance of the frequency source through intercomparison of the stability of several adjacent standards.

JPL has recognized the advantages of an ultra-stable distribution system for the past several years, and efforts have been underway to develop a technology to enable a centralized frequency and timing facility. Early in the inception of this concept it was recognized that optical fiber was the most effective media for this application. This is primarily because optical fiber has superior qualities with respect to stability, immunity to Radio Frequency Interference (RFI) and Electromagnetic Interference (EMI), and ability to transmit high frequency signals over tens of kilometers without repeaters.

JPL initiated development of fiber-optic distribution systems for precise time and frequency as a task in 1979. This early work was reported at PTTI in 1980 and 1981 [Ref. 1 and 2]. Since that time, it became apparent that it would be necessary to use single-mode fibers operating at 1300 nm wavelength to distribute stable high frequencies between stations. This was because of the lower loss, wider bandwidth and theoretically reduced delay change with bending which are associated with single-mode fiber operating at this wavelength. Therefore, a single-mode fiber capability was developed at JPL which led to the experiment described in this paper.

After the experiment was completed the link was set up for one-way distribution of the signal from DSS-13 to DSS-12 and was used as the station reference for a successful connected element interferometery experiment. The two station references are coherent to better than 1.5×10^{-15} at 1000 seconds averaging times because of the improved Signal-to-Noise Ratio (SNR) and stability of the link over the shorter one way path length. This degree of coherence enables the observation, over a short baseline, of interference fringes from a noise source such as a star or a quasar with a resolution which is limited by signal delay instabilities due to variations in the troposphere.

II. Fiber-optic System

A fiber-optic cable containing six (6) fibers was buried between DSS-13 and DSS-12, a distance of approximately 7 km. Two of the fibers in this cable are the first single-mode fibers manufactured by Corning Glass Works to be used in a non-military installation. They have 8.5 micron core diameter, 125 micron cladding diameter and are designed to operate at 1300 nm wavelength. The experiment was performed on these fibers.

One of the first concerns in trying to achieve ultra-stable frequency transmission through a cable is ensuring that delay instabilities in the cable are minimized as much as practical by such passive means as location and method of cable installation before electronic stabilizing systems are employed.

In order to minimize temperature variations, the cable was buried to a depth of 1.5 meters, as deep as practical with commercial equipment. The cable was plowed at a rate of about 3 kms./hour directly into the ground with a non-vibrating cable plow after the ground had been pre-ripped. This was to keep stresses on the cable to a minimum. Fusion splicing was used to avoid splice reflections which can reduce the effectiveness of a cable stabilizer.

The average splice loss was 0.3 dB and the total loss in each of the two single-mode fibers was approximately 14 dB. This includes splice loss and a loss of 3 dB in a directional coupler at one end of the fiber. It also includes mismatch losses, which are a result of the cable fibers having a slightly different core diameter than the pigtail fibers. The pigtails have factory installed connectors and are used to terminate the cable.

Early in this program the characteristics of various fiber-optic cables were measured and loose tube cable construction was found to have the lowest temperature coefficient of delay, about 7 ppm/°C [Ref. 3]. Loose tube cables contain a number of tubes that hold one or more fibers each. The tubes have a much larger diameter than the fiber or fibers they contain, so stress on the fibers is minimal. The tubes are filled with gel that keeps moisture out and provides isolation from acoustical vibration and shock.

A commercial fiber-optic transmitter manufactured by the Grass Valley Group, a Tektronix company, was used. It is designed to transmit television signals and was modified at JPL by by-passing the filters and DC restorer circuit to enable it to transmit a 100 MHz sinewave signal. The transmitter uses a 1300 nm single-mode semiconductor laser that emits 0.5 mW of optical power into the optical fiber. It contains electronic circuitry to control the optical output power of the laser and to keep its temperature constant.

The receiver was designed and fabricated by the Time and Frequency Systems Research Group at JPL. It has 400 MHz bandwidth which results in good temperature stability, and long term phase stability. It remains linear under the large signal conditions encountered in this application. This provides the maximum possible signal to noise ratio, and therefore the best short term phase noise.

A schematic of the receiver is shown in figure 1. It contains a PIN photodiode, a bias circuit, a decoupling circuit and a multimode fiber pigtail. The optical input is coupled to the PIN photodiode through a multimode optical fiber. The PIN photodiode is an Indium Gallium Arsenide (InGaAs) device. Biasing is provided by a low noise voltage source [Ref. 4] which provides extremely high rejection of spurious signals and power supply hum. The bias circuit consists of a constant current diode and a low noise zener diode. Two wideband transformers loaded with their characteristic impedances provide wideband high impedance decoupling to the photodiode. The output is coupled through an SMA RF connector to a low noise wideband amplifier with 50 ohms input impedance.

III. Terminal Equipment Phase Noise

The phase noise of the fiber-optic terminal equipment was measured before it was taken to the Goldstone DSCC. Figure 9 shows the measurement system used and figure 10 shows the measured double sideband phase noise, $S\phi(f)$, vs. frequency offset from a 5 MHz carrier. The signal-to-noise ratio for typical fiber-optic systems currently in use is about 120 dB/Hz and is independent of the RF modulation frequency. The measured phase noise is consistant with this value.

The laser diode noise in a typical fiber-optic link is predominate until the optical loss approaches 30 dB at which time the receiver input noise begins to be seen. Therefore, the SNR of such a fiber-optic link remains nearly constant until the link loss approaches 30 dB, and since phase noise and Allan variance are related to the SNR it can be assumed that the terminal equipment contribution to the instability of the link is nearly constant until the link loss approaches 30 dB. It was for this reason that no attempt was made to measure the phase noise of the terminal equipment under small signal conditions. A fiber-optic pigtail 3 meters long with connectors at each end was used, connecting the fiber-optic transmitter to the fiber-optic receiver for these phase noise measurements.

IV. Fiberoptic System Configuration

Figure 2 shows the the fiber-optic link configuration used for the experiment. An RF power divider splits the RF reference signal from the hydrogen maser frequency standard, at DSS-13, into two signals. One of the signals is connected to the fiber-optic transmitter and the other signal is connected to the reference input of the phase stability analyzer. The signal going to the fiber-optic transmitter modulates the optical carrier and the resulting optical signal is transmitted to DSS-12, where it is connected to the other fiber, and returned to DSS-13. At DSS-13 the optical signal is detected to recover the 100 MHz RF signal, which is amplified to the required level and then connected to one of the other ports of the stability analyzer.

V. Stability Analyzer

A block diagram of the stability analyzer is shown in figure 3. A 100 MHz reference signal derived from the hydrogen maser frequency standard is applied to the analyzer through an isolation amplifier. An RF power splitter splits the 100 MHz reference signal into two equal amplitude signals. An offset synthesizer offsets one of these signals by 1 Hz resulting in a frequency of 99,999,999 Hz. An RF mixer multiplies the 99,999,999 Hz signal and the 100 MHz reference signal and produces a difference frequency of 1 Hz, plus the phase noise of the signal under measurement. This 1 Hz output signal passes through a low pass filter, which has gain, to a zero crossing detector. The signal out of the zero crossing detector is analyzed in a microprocessor which provides Allan deviation data at 1, 2, 4, and 8 x 10^n seconds, where "n" is an integer ≥ 0.

VI. Measurement Method

The stability analyzer measured the frequency stability (Allan deviation) of the output signal from the roundtrip fiber-optic link, using the input signal to the fiber-optic link as the reference. The phase difference between the two signals was also monitored and recorded.

Figure 6 shows a simplified block diagram of the test setup. For this test all the terminal equipment and test instrumentation were located at DSS-13 and a second fiber, identical to the first, was used to complete the 14 km round trip between DSS-13 to DSS-12 and back to DSS-13. It is important to note that the data gathered was for the entire round trip including terminal equipment.

The noise floor of the measurement equipment was determined by bypassing the entire fiber-optic link and using a coaxial attenuator in its place to maintain identical signal levels to the test equipment. Figure 7 shows the resulting Allan deviation data which is marked "N.F." (noise floor). Notice the deviation from a $1/\tau$ slope at τ's > 10 seconds. This is primarily due to thermal and vibrational characteristics of the test environment on the stability analyzer and test cables.

An existing clean-up loop with a noise bandwidth of 5 Hz was used at the output of the fiber-optic link to reduce the bandwidth and the measured noise power of the received signal. The noise floor of the test system, with the clean-up loop only, was measured and is shown in figure 7 marked "C.U.L." (clean-up loop).

An additional measurement was performed using a short piece of fiber-optic cable at the test location in order to determine the stability of the terminal equipment only. This is shown in figure 7 marked "T.E." (terminal equipment).

VII. Test Results

Figure 8 shows the Allan deviation for the roundtrip fiber-optic link, including the clean-up loop. The $1/\tau$ slope portion of the graph where τ is less than 100 seconds is primarily set by the signal-to-noise ratio of the fiber-optic link. For τ's > 100 seconds the Allan deviation does not decrease at a $1/\tau$ slope as expected, but shows a "hump" around 400 seconds averaging time.

The frequency stability of signals passing through cables which are subjected to temperature cycling is expected to be degraded. This degradation shows up on Allan variance plots as a feature we shall call a "hump". It usually occurs between 100 and 1000 seconds which corresponds to the cycling time of the air conditioning. The time constant of the cable, the length of the exposed cable, and the magnitude of the temperature variation determines the magnitude of the "hump". The "hump" is usually broad because the cycling time is not constant.

The cyclic phase change responsible for the observed "hump" in the Allan variance curve was observed and recorded. It appeared to be a result of temperature changes in the plenum at DSS-12. The air conditioning at this

location has a cycle period of about 1080 seconds, and the peak to peak temperature variation is about 3°C. The length of the exposed cable in the plenum is about 45.7 meters roundtrip and the cable has a temperature coefficient of 7 ppm/°C.

The expected phase variation as a result of this temperature change was calculated using the above values. Assuming zero time constant for the cable, the phase change in degrees as a result of a change in temperature is,

$$\theta = 1.71 \times 10^{-12} L \alpha T f_o \tag{1}$$

where L=the affected length of cable in meters,

α = the temperature coefficient of delay of the cable in ppm/°C,
T = the change in temperature in °C and
f_o = the operating frequency.

Evaluating this equation using the above values yields $\theta = 0.164$ degrees, which is about twice the variation measured. However integration of the temperature variation as a result of the finite time constant of the cable could account for the difference. The time constant of this cable was calculated from this data to be 5 min. This is not unreasonable since co-axial cable of approximately the same size, but with more mass, has a time constant of $\approx$ 20 min.

To verify that this effect was what was actually observed, the phase of the round trip signal was compared to the reference signal and monitored at DSS-13. The temperature in the plenum at DSS-12 was also monitored at the same time. A strong correlation was observed between the variation of temperature and the variation of phase. In the evening, when the outside temperature is lower, the air conditioning in the DSS-12 plenum is turned off and outside air is used to cool the building. During this period the temperature did not cycle and the observed phase variations at DSS-13 disappeared. This was a further indication that the observed phase variations at DSS-13 were a result of the temperature variations in the plenum at DSS-12. The plots of phase at DSS-13 and temperature at DSS-12 are shown in figures 4 and 5 respectively.

As mentioned before, the link was set up for one-way transmission of the hydrogen maser reference signal from DSS-13 to DSS-12 to provide a stable reference for DSS-12. The stability of the one-way trip cannot be measured because there is no independent reference at the far end of the link. However, it can be estimated for the $1/\tau$ region of the curve from the relationship between the Allan variance and the signal-to-noise ratio of the signal being measured [Ref. 5].

$$\sigma = \frac{1}{\omega\tau} \qquad \frac{P_n}{P_s}, \tag{2}$$

where, ω = the angular operating frequency,
τ = the sampling interval,
P_n = the noise power in the signal being measured,
P_s = the signal power.

Using the SNR's measured at DSS-12 and DSS-13 (110 dB/Hz and 85 dB/Hz respectively) and the above relationship we estimate a theoretical improvement of 25dB for the one way trip for averaging times less than 10 seconds. This improvement will not be fully realized because the clean-up loop has a bandwidth of 5 Hz corresponding to a stability of only $1X10^{-13}$ for 1 second averaging times. A clean-up loop having the proper bandwidth is being designed.

It was also observed that bending the fiber resulted in phase changes of several degrees at 100 MHz. This observation was unexpected based on experiments performed earlier and the results of a literature search. The change should have been much smaller than observed.

If this effect cannot be eliminated or greatly reduced it could preclude the use of optical fibers in applications that require the cable to bend such as in an antenna wrap-up.

VIII. Discussions

The experiment reported here has generated a number of new and interesting questions:

Why does the phase of a signal transmitted through the fiber-optic link change so much when the fiber is bent? According to the theory, [Ref. 6] the change in delay of the fiber should be much smaller. One may speculate that AM to PM conversion in the measurement system could be responsible for the change in the delay, or it could be that light reflected back into the laser changes its wavelength resulting in delay variations due to dispersion in the fiber. A third possibility is the effect of birefringence in the fiber. However, the most probable cause of this apparent group delay change is distortion of the transmitted waveform due to light reflected back into the laser diode from the fiber.

If light reflected back into the laser from reflections in the fiber is the major cause of phase change with bending then we must ask the following questions. Is there a practical way to reduce the reflections? How much can they be reduced?

Another question that was left unanswered by the experiment is, "How stable is the buried cable ?". The signal-to-noise ratio of the laser, temperature variations, and floor vibrations appear to account for most of the frequency instability we measured. If this is true we have not yet seen the delay variations in the buried portion of the fiber-optic cable and we must reduce these other instabilities in order to measure the stability of the buried cable.

Increasing the time constant of the exposed fiber-optic cable, isolating the equipment from vibrations, and reducing the phase change in the link that results from bending the cable should improve the frequency stability of the fiber-optic link to a level that makes measurement of the stability of the cable's buried portion possible.

It is desirable to use fiber-optics to distribute reference frequencies through a moving interface. Therefore, experiments are under way to identify and rectify, if possible, the delay change as a result of bending

the fiber.

Plans are being made to use fiber-optics to connect all of the Deep Space Stations in the Goldstone Deep Space Communications Complex to a common frequency reference to permit coherent arraying of all of the antennas in the complex.

IX. Summary

A 100 MHz reference frequency from a hydrogen maser has been distributed over a 14 km distance on an unstabilized single-mode fiber-optic link having a stability of 1.5×10^{-15} for 1000 seconds averaging time. This link is providing an ultra-stable reference signal to DSS-12 from DSS-13 over a distance of 7 km. This reference is more than 2 orders of magnitude better than the station Cesium beam reference normally used at DSS-12. This capability has permitted extremely high resolution coherent interferometry measurements to be made using the two stations.

This experiment has provided the data necessary to greatly improve the stability of reference frequency distribution systems. However, there is still much work to be done to achieve the ultimate transmission stability goal of 10^{-18} stability for 1000 seconds averaging time.

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References

1- G. Lutes, "Optical fibers for the distribution of frequency and timing references", Proceedings of the 12th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, pp 663-680, NASA Conference Publication 2175, Goddard Space Flight Center, Dec. 1980.

2- G. Lutes, "Development of optical fiber frequency and time distribution systems", Proceedings of the 13th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, pp 243-262, NASA Conference Publication 2220, Naval Research Laboratory, Dec. 1981.

3- L.A. Bergman, S.T. Eng, A.R. Johnston and G.F. Lutes, "Temperature dependence of phase for a single-mode fiber cable", Proceedings of Third International Conference on Integrated Optics and Optical Fiber Communications, pp. 60, OSA-IEEE, April 27-29, 1981, San Francisco, CA.

4- G. Lutes, "Stable low noise voltage source", DSN Progress Report 42-47, pp. 89-93, Jet Propulsion Laboratory, Pasadena, CA, July and August 1978.

5- L.S. Cutler and C.L. Searle, "Some Aspects of the Theory and Measurement of Frequency Fluctuations in Frequency Standards", Proceedings of the IEEE, special issue on Frequency Stability, Vol. 54, pp. 136-154, February, 1966.

6- K.Y. Lau, "Propagation path length variations due to bending of optical fibers", The Telecommunications and Data Acquisition Progress Report 42-63, pp 26-32, Jet Propulsion Laboratory, March-April, 1981.

QUESTIONS AND ANSWERS

DAVID ALLAN, NATIONAL BUREAU OF STANDARDS: The trend that you saw in that temperature cycle variation seems to me to also be a significant concern. Do you know the cause of that?

MR. LUTES: That was mostly due to the terminal equipment and the portion of the cable that was not buried. We looked at it long enough that we should have seen some diurnal variation if it was there. Apparently it was masked by the noise and drift that we see near the terminals where the cable is not under the ground. We think that we can improve that quite a bit.

MR. ALLAN: The next question is; can you give us a feeling for cost, per foot or per nanosecond?

MR. LUTES: The cable itself, using the 24 fiber cable that we are putting in now as a basis, is eight dollars per meter. It cost between three and five dollars per meter to install it. That is buried five feet deep, if you don't have a lot of things to go through and around and under. It is not very expensive. In fact, it is cheaper than the microwave link that we are replacing. It will also carry all the communications for the station.